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An emphasis is placed on the remote platform dynamics. Performance goals are discussed and nominal head trajectories generated for use in a simulation study which was conducted to determine if these goals are achievable. Simulation and experimental results demonstrate that the electromechanical pan and tilt prototype approaches the desired performance goals. An analytical formulation of the pan and tilt dynamics is also given.

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A HEAD COUPLED SENSOR PLATFORM FOR TELEOPERATED GROUND VEHICLES

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ABSTRACT

This paper describes a remote vision system applicable to the teleoperation of unmanned ground vehicles. The features of the remote vision system are presented along with a description of its components: a sensor suite, a head slaved platform and a head mounted display.

An emphasis is placed on the remote platform dynamics. Performance goals are discussed and nominal head trajectories generated for use in a simulation study which was conducted to determine if these goals are achievable. Simulation and experimental results demonstrate that the electromechanical pan and tilt prototype approaches the desired performance goals. An analytical formulation of the pan and tilt dynamics is also given.

1. INTRODUCTION

The Naval Ocean Systems Center (NOSC) has developed and utilized remotely operated systems for numerous applications involving subsea, land-based and airborne vehicles[1,2,3]. Several of these systems have been developed with a characteristic referred to as remote presence or telepresence. Telepresence systems allow human operators to project their sensory, motor and cognitive skills to remote and potentially hostile environments while giving them the sensation of being present at the remote location[1,4,5]. The faithful reproduction of sensory information, and the design of transparent remote system controls, determines the degree of telepresence experienced by the operator.

A critical attribute of a telepresence system is its remote vision system. NOSC has developed several land-based remotely controlled systems which incorporate telepresence vision concepts. These include the Advanced Teleoperator Technology Vehicle (ATTV)[1] and the Teleoperated Vehicle (TOV)[6] (shown in Figure 1) developed for the Marine Corps' Unmanned Ground Vehicle Program. Both systems provide a stereoscopic display to the operator using head mounted cathode ray tube (CRT) monitors, and allow the operator to aim stereoscopic video cameras using head motions. This configuration permits natural, hands-off vision system control, freeing the operator's hands and attention to attend to other tasks.

2. REMOTE VISION SYSTEM

Video technology is widely used in the operation of remotely contolled land vehicles. Due to the inherent tradeoffs involved in selecting the visual field of regard and resolution, most remotely operated systems incorporate some means of changing the camera direction, in addition to using variable focal length lenses. Joystick control of a pan and tilt mechanism is one of the most common methods employed for controlling camera position. Some systems utilize multiple fixed cameras pointing in different directions in conjunction with multiple monitors to display the images to the operator. Other methods, such as steering slaved cameras[7] where the pointing direction of the cameras is slaved to the direction of the steering wheel, have been studied in attempt to simplify the operator interface.

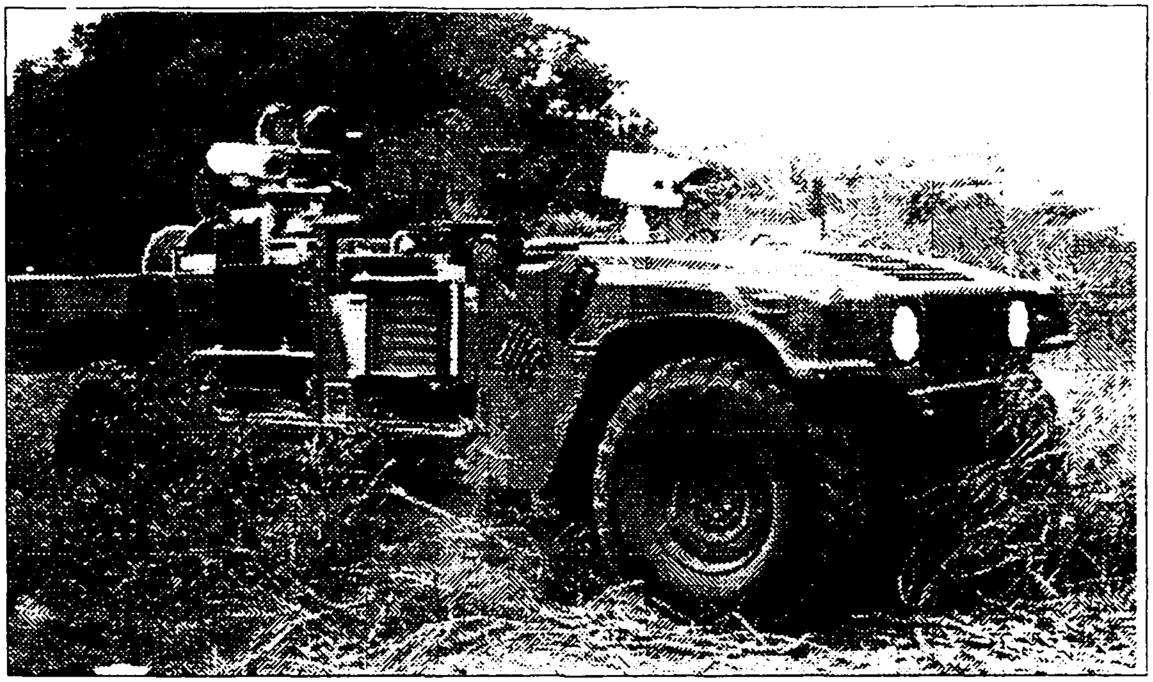

Figure 1. *UNMANNED GROUND VEHICLE: TELEOPERATED VEHICLE (TOV)*

The telepresence concept attempts to make the display and control interfaces to the operator as transparent as possible. This allows the operator to sense the remote environment much as if he were actually there. Stereoscopic video is employed to furnish the operator a three dimensional image of the remote environment which enhances his depth perception capabilities[8]. Certain off road obstacles have been noted to be undetectable without the use of three dimensional imagery (e.g., certain drop-offs and/or ledges).

As an example of the potential benefits of a telepresence display, consider the situation of an operator of a remote vehicle approaching a crossroad. With limited field of regard provided by the camera(s) one can only see a short distance down the approach avenues without changing camera direction. The operator using a telepresence system would naturally, almost subconsciously from years of experience in operating a car, turn his head to look to the left and right to ensure clear passage. Placed in a similar situation, the driver using a joystick aimed vision system would need to consciously go through several distinct steps (stopping or slowing the vehicle, panning the camera left and right and then back to the driving frame, and resume travel) to ensure no cross-traffic.

The telepresence vision system described here is very similar to prior ones developed at NOSC with the exception that the remote pan and tilt platform uses electromechanical actuation as opposed to prior systems which are electro-hydraulic.

The major features of this remote presence system are:

* Isomorphic coupling of the sensor suite to the operator's head movement.

* Providing situational awareness through visual and aural cues.

* Stereoscopic vision for enhanced obstacle detection in the remote environment.

* Providing the operator with the ability to project voice into the remote locale.

This full telepresence audio visual system consists of four primary elements: a head mounted display, a head orientation sensor, a remote sensor suite and a pan and tilt servo-mechanism. The complete system is shown in Figure 2.

3. HEAD MOUNTED DISPLAY

The head mounted display (HMD) developed at NOSC is utilized for this application[9]. The HMD incorporates two 1" diameter, high resolution CRT's. The CRT's convert video signals from the remote environment into a visual image presented to the operators eyes via optical eyepieces. The two 2-dimensional images must be closely matched in size and orientation so that the operator's eyes can comfortably fuse the two images into single 3-dimensional (stereoscopic) virtual image. Full stereo overlap with a 40° horizontal field-of-view is achieved using this binocular visual display.

An Aviator's Night Vision System mount is used for attaching the image sources to a helmet worn by the operator. Eyepiece and mount adjustments allow different drivers to adjust the HMD for their individual head geometry and visual acuity (except for astigmatism).

The helmet also provides audio communication features (headsets, microphone and push to talk switch) which are required in most telepresence applications. Head orientation is obtained using an electromagnetic sensor mounted on top of the helmet. This sensor provides three-dimensional noncontact sensing of the head's orientation within orthogonal magnetic fields generated from an electromagnetic source mounted directly above the operator's head.

4. REMOTE SENSORS & PLATFORM

The remote platform is comprised of a sensor suite and an electromechanical pan and tilt. This section reviews the components used on the sensor suite, the performance requirements and the head tracking servomechanism.

4.1 REMOTE SENSOR SUITE

The remote sensor suite consists of two cameras arranged in a stereo pair configuration, a pair of microphones and a speaker. As shown in Figure 3, the CCD cameras are mounted on optical alignment

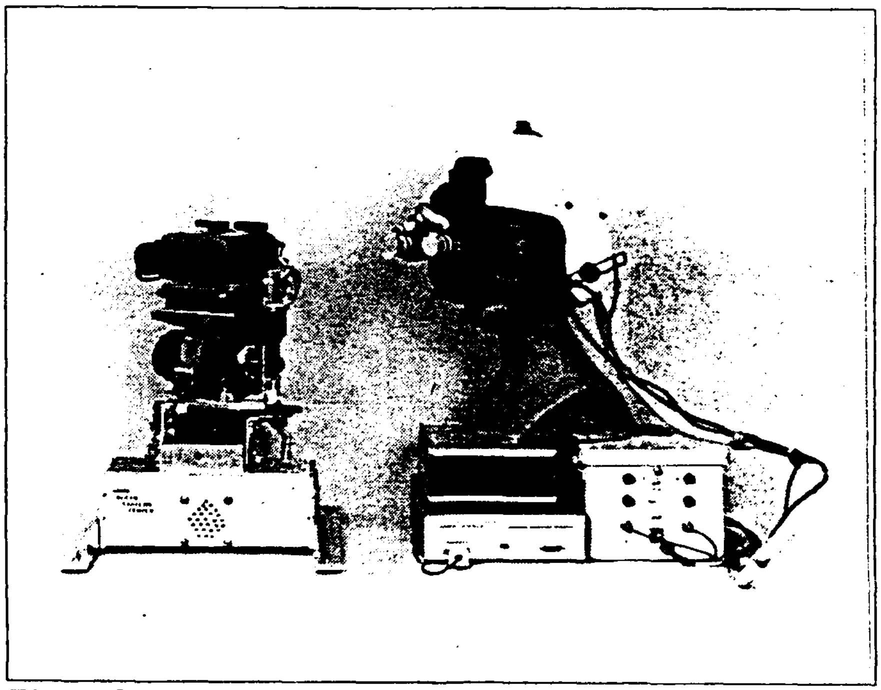

Figure 2. REMOTE PRESENCE AUDIO-VISUAL SYSTEM

stages to facilitate pitch, roll and convergence angle adjustments required for proper stereoscopic video operation.

The microphone and camera placement locations were selected based upon human factor data supplied by Mil-Std-1472C for 95th percentile ground troops and aviators. The microphones are positioned in rubber pinnae which are mounted on the platform. The use of artificial pinna separated the same distance as a human's provides the operator with natural binaural hearing to distinguish the directionality of aural cues at the remote locale. A speaker is mounted on the pan and tilt base for remote communications.

The remote cameras are high resolution monochrome charge coupled devices (CCD's). Auto-iris lenses with a 40° horizontal field-of-view are utilized to match to the field-of-view of the HMD. This provides the operator with a 1:1 spatial (orthoscopic) correspondence of the remote scene and allows him to remotely view objects much as if he were actually present at the sensor suite location. That is, the apparent visual angular subtense of an object appears to the operator to be the same as if his eyes were located at the remote camera location.

4.2 DYNAMIC REQUIREMENTS

Initial head tracking requirements were estimated as a velocity of 360°/sec and an acceleration of $1000°/sec^2$, with no overshoot. These estimates are based on average values of what was considered nominal head azimuthal velocity and acceleration. However, the actual peak velocities and accelerations attained during head motion are quite higher. Recently, experiments have been conducted which measured pilot head motions during simulated air-to-air combat scenarios[10]. The pilot wore a Kaiser Agile Eye HMD and attained peak velocities and accelerations of 344°/sec and $2452°/sec^2$, respectively, in elevation and 601°/sec and $4753°/sec^2$, respectively, in azimuth. These experiments imply that the pan and tilt servomechanisms should have approximately twice the estimated bandwidth to track peak velocities.

For simulation purposes, hypothetical nominal head trajectories have been generated. A typical azimuthal trajectory based on a ramp-step-ramp velocity profile is shown in Figure 4a. A smooth velocity profile was calculated using a quintic polynomial and the initial and final conditions of head motion in azimuth. The trajectory generated by these conditions and structure is shown in Figure 4b.

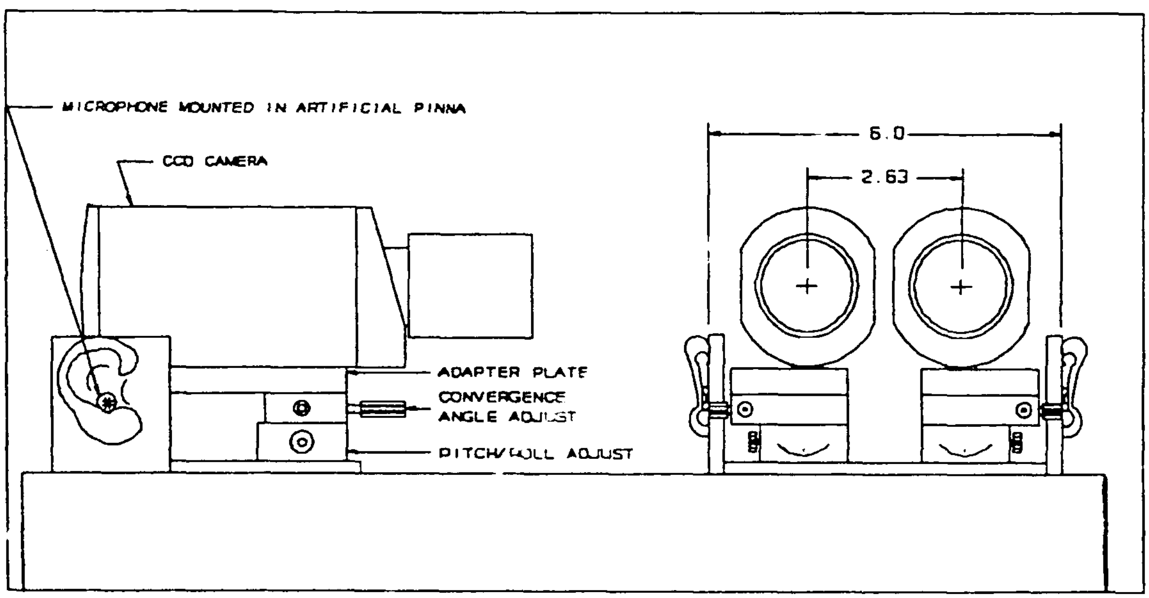

Figure 3. *SIDE AND FRONT VIEW OF THE REMOTE SENSOR SUITE*

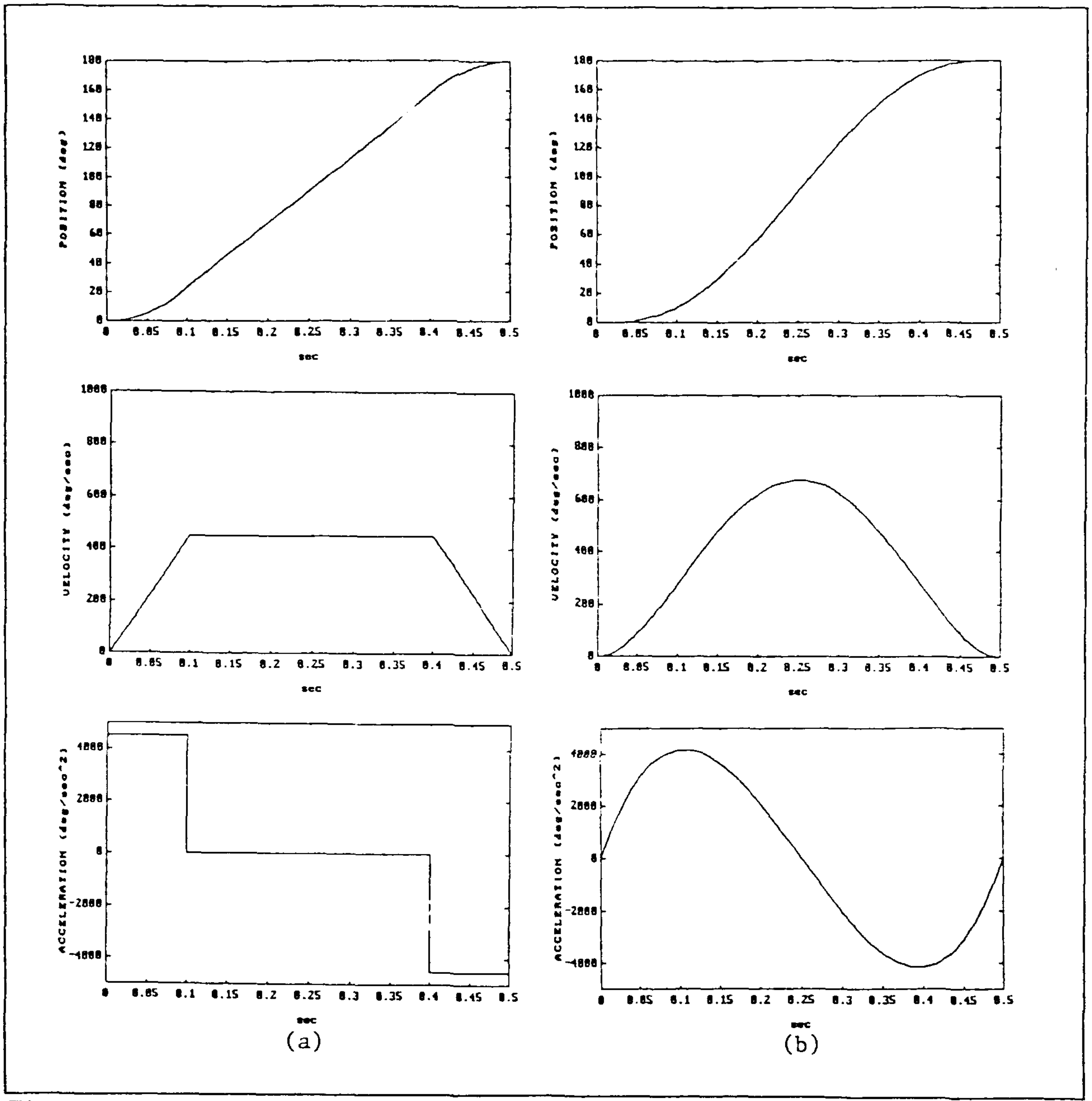

***Figure 4**. HYPOTHETICAL HEAD TRAJECTORIES:*
(a) RAMP-STEP-RAMP and (b) QUINTIC POLYNOMIAL

4.3 THE REMOTE PLATFORM

A prototype electromechanical pan and tilt has been developed as shown in Figure 2. A DC motor attached to a Dojen epitrichoidal gearhead actuates each joint. This particular motor/gearhead combination can achieve no-load velocities in excess of 500°/sec. The gearhead is a high precision device which contains essentially no backlash and a small degree of hysteresis. Position and velocity feedback are both provided for control.

Each axis is idependently controlled utilizing proportional gain control with velocity damping. This is implemented using a servo amplifier to close the loop. Integral control action is unnecessary since the human operator acts to integrate out steady state errors. A general block diagram of the basic control scheme with the coupling dynamics is shown in Figure 5.

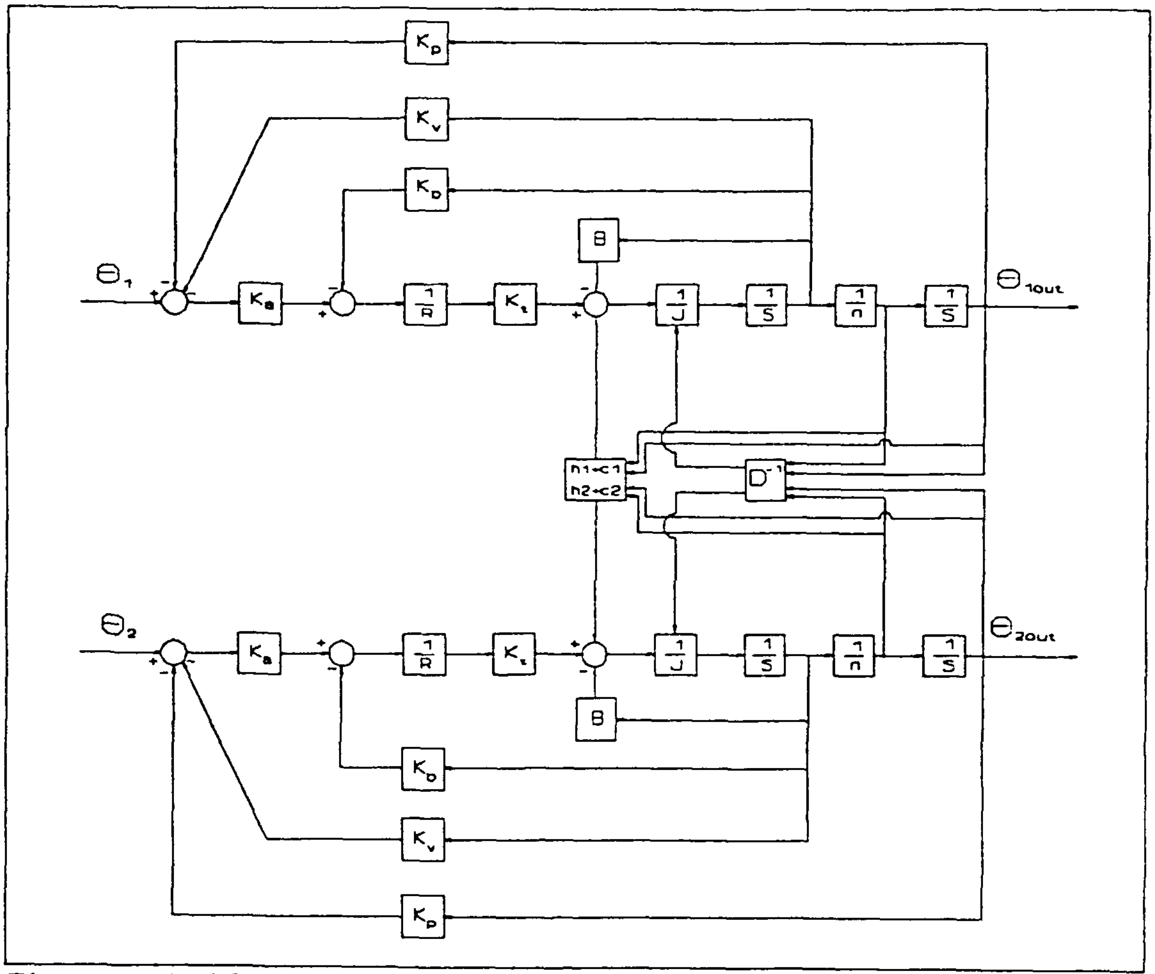

Figure 5. *BLOCK DIAGRAM OF PAN & TILT CONTROLLER*

To evaluate the effect of nonlinearities on position tracking a simulation was performed. The simulation incorporates dynamic coupling, amplifier saturation and actuator saturation.

A full analysis of the dynamics for a general pan and tilt mechanism was undertaken. The joint reference coordinate systems for the pan and tilt mechanism are assigned according to the Denavit-Hartenberg[11] representation as shown in Figure 6.

The equations of motion can be written for the applied joint torques in the general state vector form

$$\mathbf{T}(t)=\mathbf{D}(\Theta)\ddot{\Theta}+\mathbf{h}(\Theta,\dot{\Theta})+\mathbf{c}(\Theta)+\mathbf{B}\dot{\Theta}$$

where

T = n x 1 generalized torque vector applied at the n joints
D = n x n symmetric inertial matrix
h = n x 1 nonlinear Coriolis and centrifugal force vector
c = n x 1 gravity loading force vector
B = n x n diagonal damping coefficient matrix

These terms can be found using the Lagrange-Euler formulation[12] with additional assumptions imposed about the symmetry and mass distributions of the links

$D(1,1)=I_{1yy}+I_{2xx}\mathrm{Sin}^2\Theta_2+I_{2yy}\mathrm{Cos}^2\Theta_2$
$D(1,2)=0$
$D(2,1)=0$
$D(2,2)=I_{2zz}$

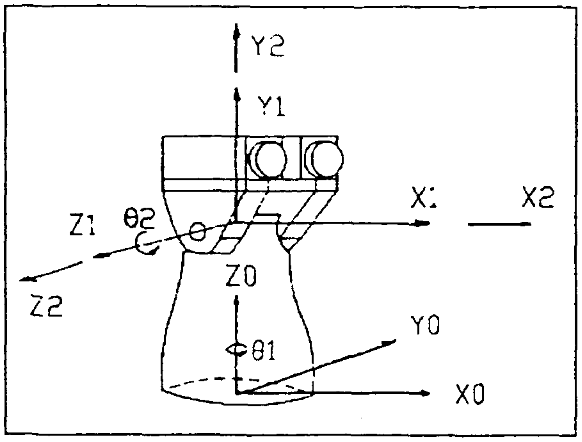

Figure 6.
JOINT REFERENCE COORDINATE SYSTEMS

$$h(1)=2(I_{2xx}-I_{2yy})\mathrm{Cos}\Theta_2\mathrm{Sin}\Theta_2\ \dot{\Theta}_1\dot{\Theta}_2$$

$$h(2)=(I_{2yy}-I_{2xx})\mathrm{Cos}\Theta_2\mathrm{Sin}\Theta_2\ \dot{\Theta}_1^{\,2}$$

$$c(1)=0$$
$$c(2)=-m_2 g Y_{2cg}\mathrm{Sin}\Theta_2$$

$$B(1,1)=B_1$$
$$B(1,2)=0$$
$$B(2,1)=0$$
$$B(2,2)=B_2$$

where

I_{ijj} = moment of inertia of link i about the jj axis
m_2 = mass of link 2 (tilt platform)
Y_{2cg}= distance to CG of link 2 along Y axis
Θ_i = angular displacement of the i^{th} link
B_i = damping of link i

The assumptions incorporated in this derivation are that the origins of the axes in the horizontal plane are located at the center-of-gravity of each link and that these axes are also coincident with the plane of symmetry for the mass distribution of each link. If each link is designed such that it is balanced and symmetric with respect to its own (local) coordinate system then the mass products of inertia become zero thereby alleviating inertial coupling effects.

For the tilt link , it was not assumed that the joint be coincident with the center-of-gravity along the vertical Y_2 axis. This allows for the overhung load condition which exists in the prototype. Appropriate modifications need to be incorporated in all I_{2ij} inertial terms should an overhung load condition exit. This is easily accomplished using the parallel axis theorem. If an overhung load is non existent then the gravity force vector **c** need not be incorporated into the analysis. Though inertial coupling is alleviated with this design approach, Coriolis torque loadings remain imparted to joint 1 (pan) and centrifugal torques are present at joint 2 (tilt).

4.4 RESULTS

Simulations were run using azimuth and elevation trajectories similar to the step-ramp-step velocity profile as shown in 4a. Figure 7 shows the simulation results for position tracking and nonlinear torque magnitudes for simultaneous azimuth and elevation commands. More specifically, Figure 7c shows the magnitudes of the Coriolis, centrifugal and gravitational torques normalized with respect to the available (stall) torque at the gearhead output shaft. As expected, the overhung load places the greatest demands on available motor torque. The gravitational loading is approximately 12% of the available torque. Both the Coriolis and centrifugal torque loadings are smaller than the gravitational torque and may be considered as dynamic disturbances to the control loop as they have little effect on tracking performance. However, these disturbances are inversely proportional to the gear ratio. If direct drive motors or low gear ratios are employed the Coriolis and/or centrifugal effects may become significant.

Experiments were conducted on the pan and tilt prototype to determine its bandwidth and tracking capabilites. The servo amps on the prototype were current limited to 50% of their rated capability thus limiting the system to 25% of its available power. This was done as a measure of protecting the amplifiers. Additional power is lost to binding due to misalignment between the motor and gearhead caused by the adapter.

The input and feedback position signals at the

servo amp were measured to characterize the pan and tilt. Thus, head tracking delays induced by the position sensor were not included in the experimental data. Test results under these conditions showed that the prototype pan and tilt has a bandwidth of approximately 0.5 Hz. in both axes. Response to a step input demonstrated classical second order behavior with less than 3% overshoot.

The pan and tilt was commanded by various sine wave inputs to observe dynamic tracking lags. A 0.8 Hz sine wave cycling over 132° resulted in a tracking lag of approximately 100 msec. Under human head motion control, cycling over 180° at approximately 0.3 Hz, dynamic lags were roughly 40-60 msec. The expemental outcomes confirmed the simulation results.

5. CONCLUSIONS

A head coupled sensor platform has been designed to operate in conjunction with a head mounted display. This results in a remote presence audio-visual system which can help provide a natural driving environment for the remote operation of unmanned ground vehicles.

High resolution stereoscopic vision and the ability to track a human's head motion are key elements of the remote presence audio-visual system. The prototype head coupled sensor platform was designed to provide high resolution video on a moderate bandwith electromechanical pan and tilt prototype.

The prototype's performance approaches the initial goals and agrees with simulation results. However, recent experiments have indicated that bandwidth requirements are twice as large as initially estimated. An improved design, currently under consideration, will incorporate components to meet this requirement.

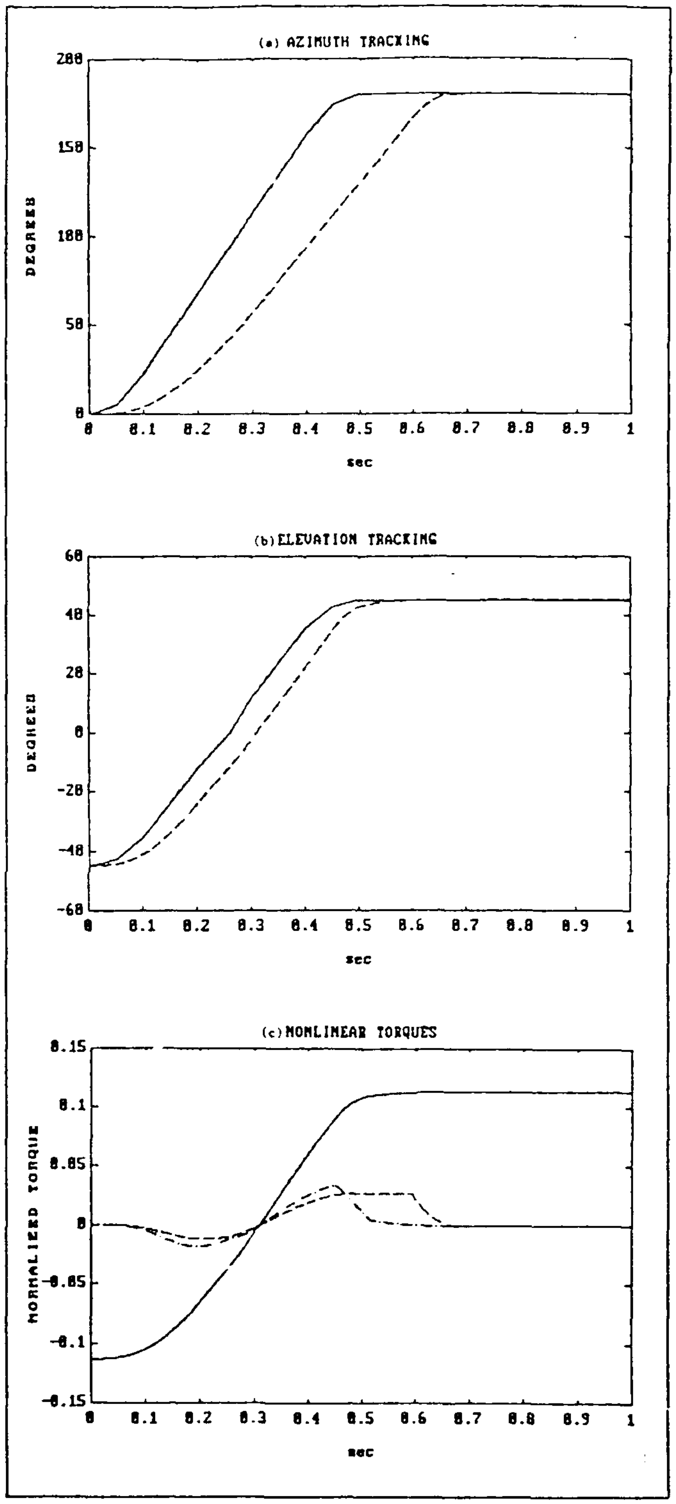

Figure 7. SIMULATION RESULTS: (a) AZIMUTH TRACKING, (b) ELEVATION TRACKING (c) THE EFFECT OF NONLINEAR TORQUES, Coriolis -.-, centrifugal ---, and gravitational —

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